Renewable and Sustainable Energy Reviews 23 (2013) 155–168

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review of energy aspects of green roofs

Omidreza Saadatian [a,*], K. Sopian [a], E. Salleh [a], C.H. Lim [a], Safa Riffat [b], Elham Saadatian [c], Arash Toudeshki [d], M.Y. Sulaiman [a]

[a] Solar Energy Research Institute (SERI), Level 3, Perpustakaan Tun Sri Lanang, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
[b] Department of the Built Environment, University of Nottingham, University Park, Nottingham NG7 2RD, UK
[c] Keio-NUS CUTE, National University of Singapore (NUS), Singapore 119613, Singapore
[d] Faculty of Engineering, Universiti Putra Malaysia, 43600 Serdang, Malaysia

ARTICLE INFO

Article history:
Received 13 May 2012
Received in revised form
14 February 2013
Accepted 18 February 2013
Available online 25 March 2013

Keywords:
Green roofs
Environmental and economic benefits
Energy
Plants

ABSTRACT

Global warming, depletion of natural resources, acid rains, air and water pollutions, and ozone depletions are some of the environmental consequences that are deemed attributable to human activities on planet earth. Sustainable practices have been therefore evolved as main remedies to tackles these issues. Green roof strategy is one of these practices that not only provides heat island amelioration and thermal comfort for occupants but also reduces energy consumption of buildings as well as add aesthetic values to the environment. This paper targets to run a review on the application of green roof strategy. The review scans a time frame from 2002 through early 2012 with a focus on energy related topics on energy related topics of green roofs. The review discussed various types of green roofs, components of a green roof, economic revenues, and technical attributes. Many general advantages and few general disadvantages of green roofs in one hand and pros and cons of green roofs with respect to energy utilization on the other hand are also synthesized. Some recommendations for future study are also proposed.

Contents

1. Introduction

Climate change and scarcity of natural energy resources [1] are topics of current interest [2]. Building accounts for 33% of global green gas emission [3,4]. Buildings also accounts for about 40% of total primary energy requirement of the USA [4], 23% of Spain,

* Corresponding author. Tel.: +60 17 2075459; fax: +60 3 8921 4593.
E-mail address: omid.saadatian@gmail.com (O. Saadatian).

1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.02.022

25% of Japan, 28% of China, 39% of Great Britain, 42% of Brazil, and 47% of Switzerland [5]. Therefore, designing more environmental friendly components of buildings leads to more energy savings and less depletion of natural resources [6]. A roof is an important component of buildings and with proper produces sustainable outputs [7]. Covering a roof with soil, wetting the soil and shading the wet soil surface were historical passive cooling practices in hot and arid climate [8].

Green roofs, in general, refer to any type of roofs that a green technology is incorporated in it. Those green technologies include vegetated roofs [9], cool roofs [10], and even some academicians included roofs with solar panels[11]. There are several names for this strategy which stems from existence of various views in its application. For instance, green roofs are named eco roofs for its ecological benefits [12,13]. It is also called roof garden or living roof by other professionals [14–17]. Green roof strategy is a sustainable design of roof which decreases storm water runoff [18–23], add more green spaces, produce more oxygen [24], and sequester carbon dioxide [25–30]. It also decreases the burden of water treatment facilities, increases the water runoff quality [15,23,27,31–38], and saves energy for cooling and heating purposes due to its insulation effects [35,39–42].

Moreover, green roof creates habitat for wildlife [43–46]. It is a remedy for heat island effect [47–51], creates recreational opportunities [52,53] and increase the roof's life [52,54]. Some green roofs use irrigated vegetation which has a profound impact on heat island [55]. Green roofs or roof gardens not only provide insulation for energy saving purposes but also prevent noise pollution [56–59]. It has been regarded as a good solution to reduce noise annoyance by road traffic [57]. That is a sustainable initiative that attracts energy scientists, architects and urban planners for the both energy conservation, and urban quality improvement. The Term of green roofs also covers balconies and terraces that have vegetations and are used as green spaces [60]. However, those balconies and terraces affect indoor spaces differently from green roofs in terms of energy. Since the initial cost of a green roof is more than three to six times of conventional roofs, the utilization of green roofs is overlooked in many developing countries [61]. Despite its high initial cost, in long term, green roofs are an economical option considering their energy saving [35,61–63].

European countries have been the paradigm in implementing this concept in their buildings and conducting research on the green roof strategy for the past 30 years [43]. Germany is regarded as the world leader in employment of green roof strategy whereby over 10% of its buildings utilizes this strategy [25,50]. The total value of green roof technology in Germany was estimated to be worth USD 77 million in the year 2008 [64]. It included 13.5 km^2 of green roofs [64]. Since the majority of green roofs research of Europe were conducted in Scandinavia, Germany, and Switzerland in which were reported in languages other than English [22], conducting a review of green roof in English is desirable.

One review of this topic has only presented the vegetation and ecology aspects of green roof and solely in North American eco-regions [43]. Another review on this topic has only focused on quantity and quality of runoff water [65]. Eventually, the last review has touched on retrofitting old buildings through use of green roofs [64]. Therefore this review focuses on energy aspect of green roofs spanning the period of 2002 until February 2012.

Since the first English report of "Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau" (FLL) i.e. "the German Landscape Research, Development and Construction Society" has been published in 2002 [43] hence the year 2002 is selected as the starting point of this review. The objectives of this paper are to review the green roof strategy in terms of energy and to identify its environmental and economical benefits and challenges as well as to cast light on the research needs of this realm of study.

2. Green roofs retrofit potential

Green roof strategy is not only a solution for new built projects but also is suggested as a lucrative and feasible solution for retrofitting projects [66–68]. In this fond, the life span of green roofs which is estimated between 40 and 55 years is important. According to Acks [69] it is 55 years, while Clark, Adriaens, and Talbot, suggested it 40 years [70]. However, Saiz et al. estimated it 50 years [71], and Kosareo and Ries [54] predicted its life span to be 45 years.

For investigating the retrofit potential of green roof, two scientists, conducted a research [66]. They compiled the information of large scale 536 commercial buildings in the Central Business District of Melbourne and evaluated the potential suitability of those buildings to undergo the roof garden retrofit [66]. Their study revealed that, although overshadowing of the roof areas and unfavourable orientation were two serious impediments, about 15% of Central Business District of Melbourne's building stocks were suitable for the green roof retrofit. Moreover, their study revealed that buildings with concrete structure are the best buildings to undergo the green roof retrofit.

In retrofitting the existing buildings with green roofs, the issue of increase of dead loads and structural failure is considered as an important obstacle. However, it was suggested that for medium-rise office buildings, which have reinforced concrete slab in the UK, additional structural modifications is not needed to undergo the green roof retrofit [72]. The same suggestion was made for medium-rise office buildings which has profiled steel decking surfaced with Plywood roof structure. They concluded that there is a high potential for retrofit of buildings with the green roof in the UK, because many of buildings have concrete slab structure and they can withstand 8–10 kN/m^2 of dead load which is adequate to support a growing medium up to 80 cm (see Fig. 1). That is why green roof strategy is suggested as a suitable retrofitting mediums to tackle energy crises to cover the poor insulation problems in old buildings [64].

It is argued that retrofitting old buildings brings more economical benefits in comparison to new buildings [64]. The reason is that old buildings are generally less well insulated. For that, they lose a lot of energy annually. The retrofitting of old buildings with green roofs brings monetary savings and environmental benefits such as reduction of carbon emissions due to lower energy consumption.

3. Green roofs attributes

Green roofs, in general, consists of four main components namely: 1—water proofing membrane and filter membranes, 2—drainage films, 3—growing medium (soil), and 4—landscape materials i.e. plants [73,74] (see Figs. 2 and 3). Some green roofs are installed over the corrugated steel deck such as gable roofs (see Fig. 3). Change of any of the mentioned components alters the efficiency of green roofs.

Green roofs have been categorized into two groups of intensive roofs and extensive roofs. The former is thicker and heavier which can grow under a wider variety of vegetations such as small trees, shrubs and bushes in substrate depth of more than 20 cm [25,52]. However, the latter can support lighter plants and needs less maintenance [31]. Intensive roof gardens are normally designed for the use of human and entertainment which requires extra structural reinforcement [75]. However, in extensive green roofs'

Fig. 1. Retrofitting old buildings without changing the structure in the UK [64].

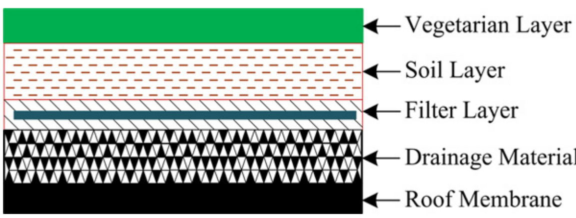

Fig. 2. Components of a typical green roof.

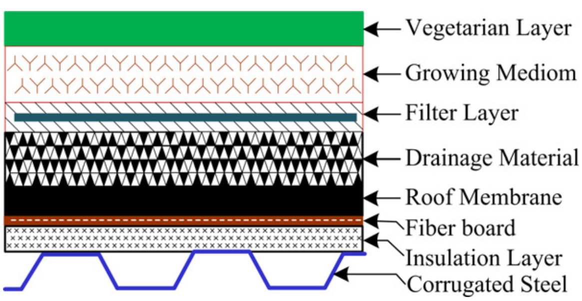

Fig. 3. Components of green roof over corrugated steel roof.

foot traffic is prohibited due to fragile root nature of landscape [54,76,77]. Intensive green roofs function much better than extensive green roofs in terms of runoff reduction and those also improve the quality of the runoff. For instance, intensive green roofs reduce runoff by 85% whereas extensive green roofs reduce the runoff by only 60% in comparison to normal roofs [54]. Likewise, intensive green roofs' runoff has three times less lead contamination, 1.5 times less zinc contamination, 2.5 times less cadmium contamination and 3 times less copper contamination [54].

4. Green roof and energy

Introducing plants and landscapes to buildings surfaces is regarded as a technique which reduces building temperature up to 20 °C and also reduces the air-conditioning energy between 25% and 80% [61]. Green roofs have been introduced as one of the most efficient medium of energy savings in building sector [78,79]. This particular type of roof reduces building energy demand through improvement of thermal performance of buildings [78,80]. Improvement of thermal performance is due to increment of shading, better insulation, and higher thermal mass of the roof system [62,78]. The main function of green roofs is to prevent the solar radiation which heats building's interior spaces. Green roofs are able to reflect 27% of solar radiation and absorb 60% of solar radiation through photosynthesis and transmit the remainder as much as 13% to the growing medium [61].

Green roof serves to provide more thermal comfort and reduces the roof surface temperature [81]. Direct shading of roof surfaces and cooling down the ambient air are two important phenomena that provide more thermal comfort. This thermal benefit is the results of consuming solar heat gain for transpiration and photosynthesis [81]. Besides, green roofs absorb lower radiative temperature in comparison to other types of roofs [81]. Green roofs combats urban heat island effects and contributes to the thermal benefits of urban areas [81–83]. According to an experimental study conducted in Japan, it was revealed that green roofs can decrease the surface temperature of the roof around 30–60 °C [81]. Green roofs save energy and, consequently, save money [84]. The amount of savings depends on different factors such as type of green roofs, depth and composition of the growing medias, climates, plant selection, type of irrigations and insulation specifications [85]. Moreover, based on Martens et al. the total amount of energy savings of green-roofed buildings is more significant for single-story structures than other types of buildings [86].

The field studies of green roofs were mostly been limited to cooling effects and to measure the surface temperature of roofs. It then felt that there was a need for a more comprehensive design tool. Architects, civil engineers, developers and building stakeholders require a design tool to be able to assess the benefits of green roofs in their own projects. For addressing this problem, Sailor, undertook a study using Energy Plus software and mathematical modelling to predict the benefits of green roof strategy. Sailor's green roof module assists building stakeholders to explore green roof design options [13]. It included thermal properties, vegetation characteristics i.e. leaf area index (LAI), height and type of plants, growing media and depth of growing medium as the main factors that can be used in mathematical model to address the mentioned short coming [13].

4.1. Effects of plant types

Green roofs benefit the buildings through direct and indirect thermal impacts. The direct effects are those which are related to the building components such as the effects of shading on reducing the surface temperature of buildings. Indirect impacts are those which contribute to buildings surroundings such as reducing outdoor thermal environment. The characteristics of the vegetation have been regarded as one of the most significant parameter of the green roof heat transfer [87,88]. It includes LAI [89], stomatal resistance (a pore found in plant functions as a gas exchange) [90], height [13], fractional coverage [13], and albedo (reflection coefficient) [13].

The LAI is an index representing the plan-form area of coverage of the leaves and depends on the plant species. It is normally in the range of 0.5–5.0 [13]. For instance, if the average parcel of a given roof surface is beneath two leaves, its leaf area index would be considered as two [13]. The fractional vegetative cover is another index which is related to LAI and calculated fraction of the green roof surface that is directly covered by plants' leaves [13]. The fractional coverage is considered significant, since it determines the amount of the radiative characteristics of the soil media in the surface energy balance [13]. The albedo is the reflection coefficient that dictates the reflectivity of the surface to the solar energy incident on a green roof surface [13]. Finally, the stomatal resistance is a biophysical unit that determines the rate of moisture transpiration of the plants of green roofs [13].

In this regards, a filed study was undertaken in Singapore to investigate the thermal impacts of an intensive green roofs in tropical climate [81]. They aimed to investigate the effects of plant types, with various leaf area indices, on the reductions of surface temperature [81]. The researchers also aimed to gauge the reduction of heat gain of green roofs as well as variation of ambient variable caused by green roofs. The study employed two sets of data loggers, and thermocouple wires to measure the surface temperatures. It also utilized two sets of data acquisition devices namely Babuc A, and sensors to measure wind velocity, ambient air temperatures, relative humidity, and global temperatures. In order to measure the solar radiation, two sets of solar meters were used. The research team used six species of various plants with different leaf area index. Those six species included: 1. *Heliconia*, 2. Spider lily, 3. *Ophiopogon*, 4. *Raphis* palm, 5. *Pandanus*, and 6. *Erythrina*.

The results of the study revealed that LAI is extremely influential in achieving higher shading effects and lower temperature. Denser vegetations such as *Pandanus*, Spider lily, and *Raphis* palm caused more shading and the temperature under them was recorded lower [81]. The results, furthermore, revealed that the maximum temperature of hard surface reached 57 °C whereas the maximum temperature of bare soils reached 42 °C. Nevertheless, the maximum temperature of spaces located under the plants did not exceed 36 °C (see Fig. 4). Likewise, the study showed that the maximum daily variation of surface temperature was less than 3 °C [81]. The maximum surface was recorded to be 26.5 °C indicating that reduction of temperature is dependent on thermal protection of plants [81].

The research team also evaluated the direct thermal effects of plants through calculating the heat flux. The *U* value index of the heat flux was calculated for tree (*Erythrina*), shrub (*Raphis* palm), turf (*Ophiopogon*), bare roof, and bare soil (without any plants) (see Fig. 5).

Bare roofs showed a higher heat flux in comparison with planted roofs and the maximum heat flux occurred around 2 pm amounting to 14.78 (W/m^2) (see Fig. 5). The results of the study also revealed that the heat transfer of the roof with bare soil is subjected to fluctuations at various time of the day (see Fig. 4). Interestingly, heat flux for the area under the shrub was appeared to be always negative during daytime (see Fig. 5). The maximum decrease of temperature after incorporating the green roofs was recorded 30 °C [81].

The research team also measured the total heat lost and total heat gain per metre square of a typical day. The results indicated that there was no heat gain under the shrub area at all. In contrast, bare roof surfaces had the highest total heat gain per metre square amounting to 336.3 kJ/m^2 (see Table 1). In terms of larger amount of total heat gain per square metre, surfaces under shrubs, surface under trees, surface under turfs, surface under bare soil showed better performance and lower heat gain in comparison to surface under bare hard roof s (see Table 1).

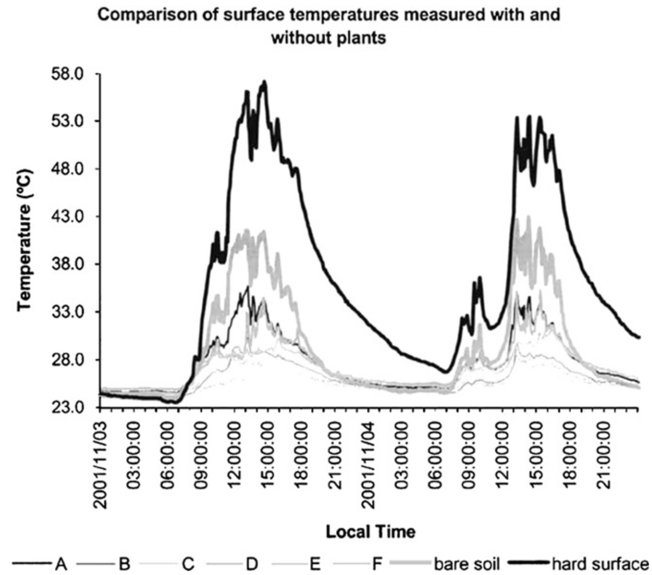

Fig. 4. Surface temperatures for *Heliconia* (A), Spider lily (B), *Ophiopogon* (C), *Raphis* palm (D), *Pandanus* (E), *Erythrina*, (F) bare soil and hard surface [81].

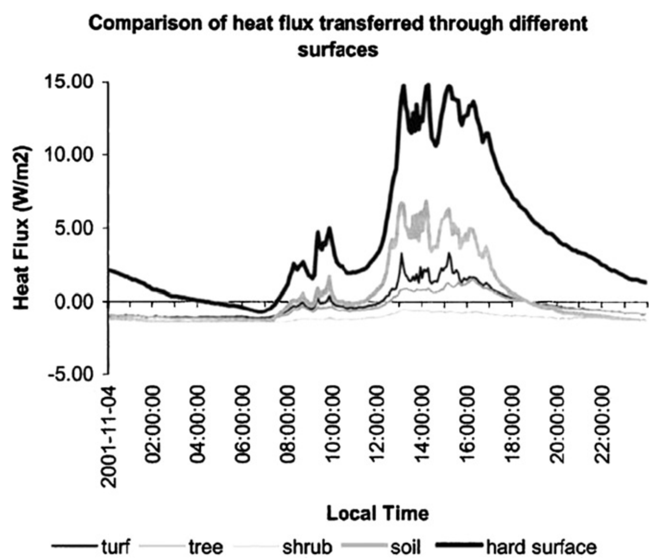

Fig. 5. Results of heat flux transferred through various roof surfaces [81].

Table 1
Results of heat gain/lost per metre square for various roof tops [82].

Type of roof surface	Total amount of heat gained over a day (kJ/m^2)	Total amount of heat lost (kJ/m^2)
Shrub	0	104.2
Turf	29.2	62.1
Tree	15.6	53.3
Bare soil	86.6	58
Hard surface	366.3	4.2

4.2. Seasonal performance of green roofs

A research team quantified the thermal properties of an inverted extensive green roof versus a traditional gravel ballasted inverted roof at Michigan State University campus [85]. They aimed to demonstrate that how roof temperatures as well as heat flux are affected by incorporating a roof garden during four seasons of the year. The research team also investigated the

credibility of other reports on the role of various influential parameters on the performance of green roofs. The parameters were solar radiation, ambient outside temperature, and volumetric moisture content of the growing medium in one hand and heat transfer and thermal differences between roof gardens and gravel roofs in another hand.

Their experimental project was located in Midwestern U.S. climate characterized by hot, humid summers. That location had also cold snowy winters and hot, humid summers along with cold, snowy winters. The green roof plants were planted on a sedum dominated shallow depth roof without irrigation. They installed a 325.2 m^2 extensive green roof on an existing building roof. The experimental building was a steel-deck inverted roof assembly insulated with extruded polystyrene. The roof was covered with a growing media and plants by laying out pre-grown vegetated mats. This mat consisted of a carrier containing at least 5 cm of proprietary media including heat expanded slate, sand, and organic matter. They also sampled and analysed the physical properties of the growing medium.

Data were collected for 1 year period from 1 September 2005 to 31 August 2006. During the data collection phase, five devices of CR10X Data logger, three AM25T 25-Channels Solid-State Multiplexors and a TDR-100 Time-Domain were employed. The devices were used in order to measure the ambient weather conditions, heat flux, soil moisture, and reflectometer temperature. Three measurement stations were installed on the gravel portion of the roof and the vegetative side of the roof, spaced 3.0 m apart. Each station had five thermocouples installed. Some thermocouples were installed on 1 m above the roof inside a non-aspirated solar radiation shield. Some others were installed on top of the gravel, on top of the insulation, on top of the roofing membrane; and inside the building directly against the ceiling. They also used a universal heat flow sensor installed on the top of the roof insulation at each measurement station.

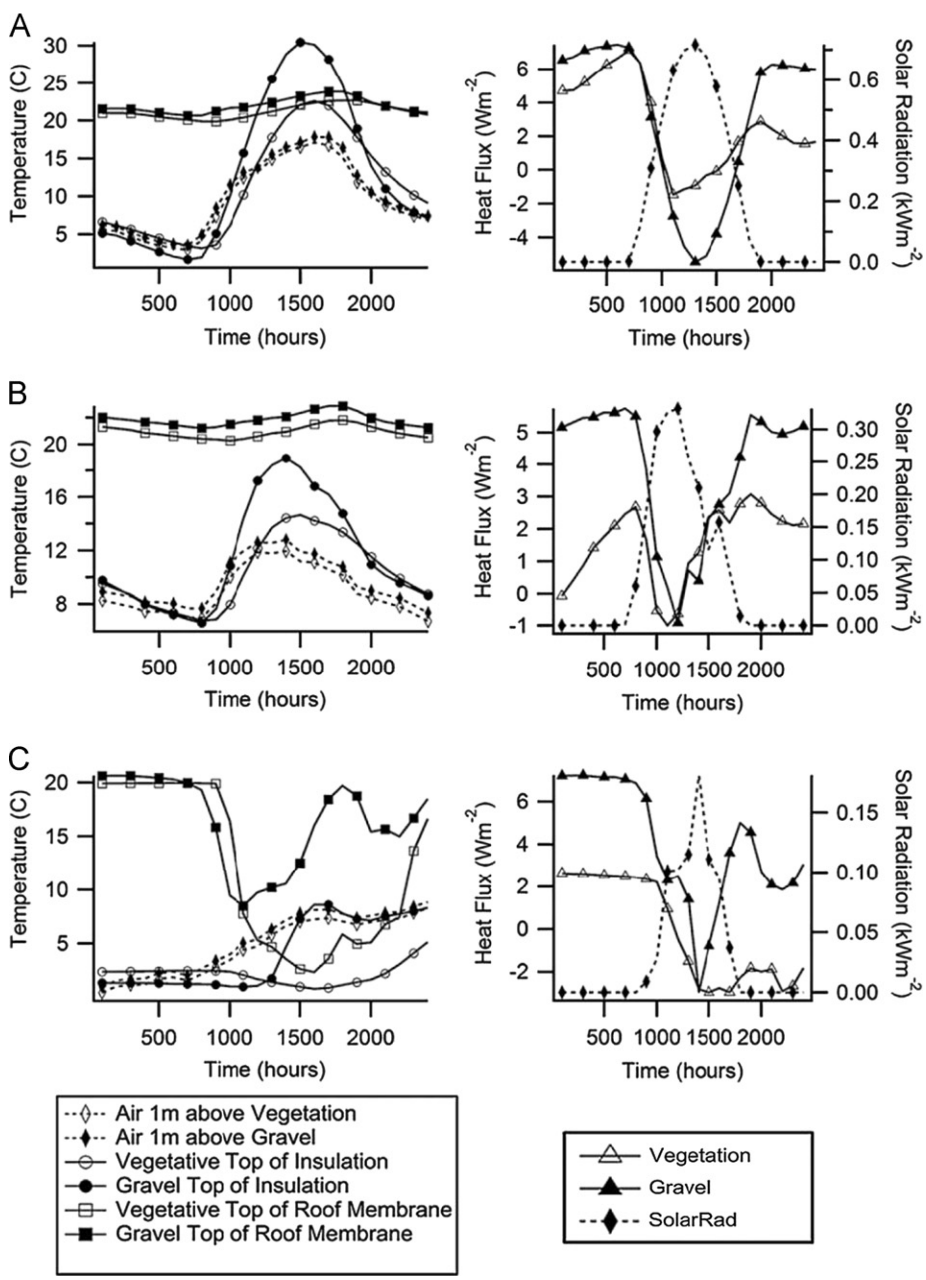

Fig. 6. Temperature and heat flux data over one day period for different environmental conditions in autumn [85]. (A) Autumn Sunny (08 October 2005); (B) Autumn Cloudy (06 October 2005); (C) Autumn Rainy (26 November 2005).

A soil moisture probe was also installed horizontally at each site. The research team had the precipitation data polled every minute, totalled and reported at hourly intervals. They excluded winter month's data, due to the inability of measuring solid precipitation. They found out that the green roof can cause reduction in temperatures of 5 °C in autumn (see Figs. 6 and 7). Besides, it was revealed that even during chilly and moist conditions, the heat flux leaving the building is lower for the green roof than the gravel roof [85].

Likewise, temperatures measured at the top of the insulation layer were found to be more variable for roofs on cold season days without snow cover than with snow cover. However, temperatures variation between green roofs and gravel roof in autumn and spring was similar (see Figs. 6 and 8). The most significant finding was that peak temperature differences between gravel roof and green roof in summer showed a maximum of 20 °C which was the largest difference in all seasons (see Fig. 9). During summer the roof garden held its efficiency by reducing heat flux through the building envelope by an average 67% during summer while in winter the reduction was only 13% (see Figs. 9 and 10). Likewise, summer cumulative monthly heat flux values demonstrated a net heat gain into the building for the gravel roof. In contrast summer cumulative monthly heat flux values for the green roof showed a cooling effect on the building (see Fig. 10).

Measuring the various variables indicated that the gravel roof generally exhibited larger fluctuations than the roof garden. Finally, the study revealed that gravel roof performed weaker in terms of maximum and minimum average monthly temperatures and heat fluxes than the green roof (see Fig. 11). Moreover, maximum and minimum average monthly temperatures of the gravel ballasted roof was more extreme than the green roof whereby the building with green roof was about 20 °C cooler in the summer than building with gravel roof. Measurement during autumn and spring seasons as well as snow covered time of the

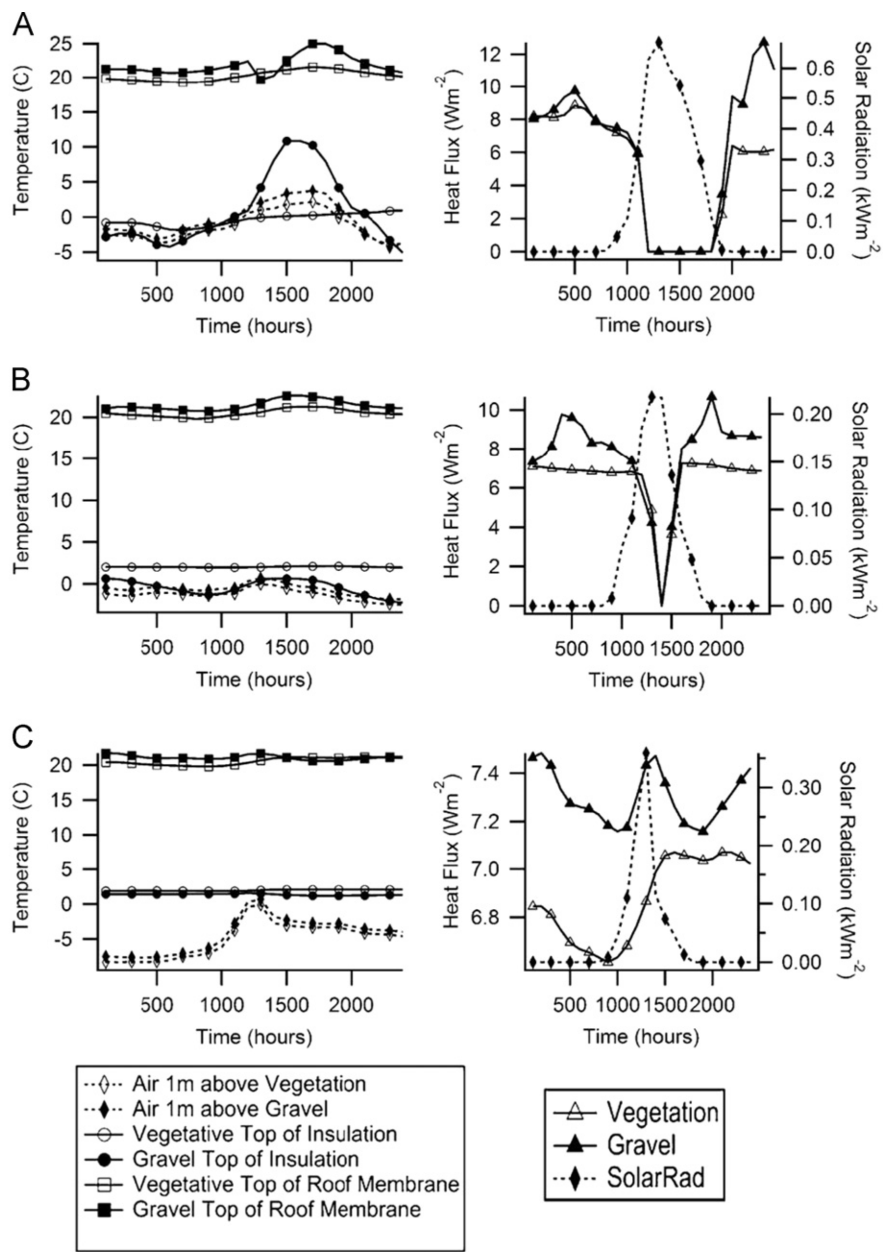

Fig. 7. Temperature and heat flux data over one day period for different environmental conditions in winter [85]. (A) Winter Sunny, No Snow Cover (21 February 2006); (B) Winter Cloudy, Green roof has snow cover, Gravel roof does not (25 January 2006); (C) Winter Cloudy, both green roof and gravel roof are snow covered (21 December 2005).

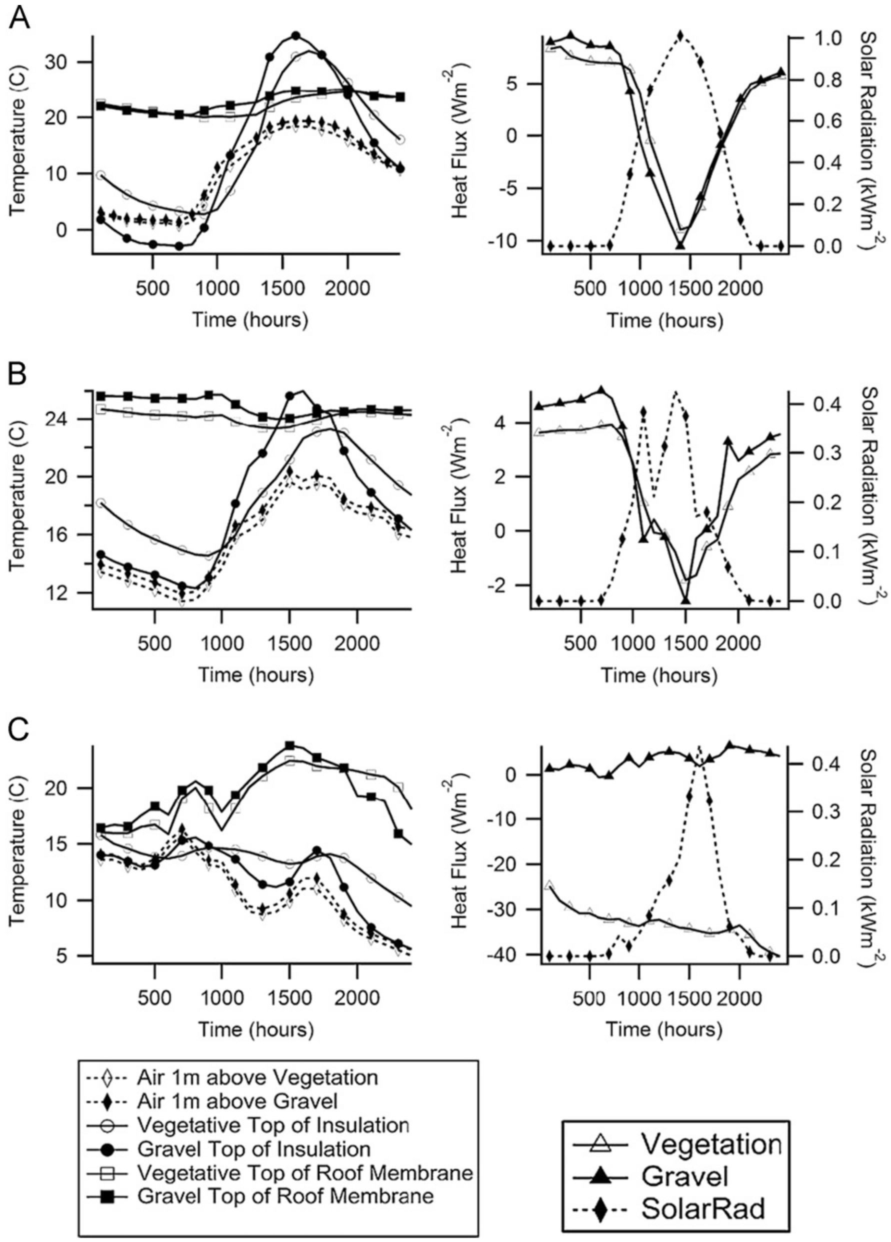

Fig. 8. Temperature and heat flux data over one day period for different environmental conditions in spring [85]. (A) Spring sunny (25 April 2006); (B) Spring cloudy (29 April 2006); (C) Spring rainy (10 May 2006).

winter proved the superiority of the green roof to the gravel roof (see Table 2).

This study concluded that the heat transfer and thermal differences between green roofs and gravel roofs depend on four main parameters during various seasons. Those are: volumetric moisture content of the soil, solar radiation, ambient outside temperature and snow. They also suggested that increasing the depth of medium and supplying irrigation enable the contractors to use plants with greater biomass and leaf area. The use of plants with greater biomass and leaf area in turn leads to higher evapotranspiration rates.

Another study conducted by Teemusk and Mandar in Estonia compared the temperature regime of a light weight aggregates based roof garden with a modified bituminous membrane roof in different season [73]. They employed an experimental method by doing measurement from June 2004 to April 2005. The results of their study revealed that a 100-mm-thick substrate layer of the roof garden can decrease the temperature fluctuations significantly in summer periods. Likewise, green roofs protect the roof's membrane from rapid cooling and freezing in autumn and spring. Moreover, a green roof provides effective thermal insulation in winter [73].

By contrast, Jim and Tasang [91] conducted an experimental study on a building located in the heart of a densely developed urban district in Hong Kong. The result of their study imparted that green roof triggers upward heat flow from the substrate to the ambient air in winter. Therefore, they claimed that green roofs create demands for more energy consumption to warm the indoor air in winter [91].

4.3. Green roofs and cooling load

Green roofs have been regarded as an efficient solution of reducing cooling load [42,92]. Based on a study conducted in Singapore by Wong et al. it was revealed that green roofs can contribute to reduction of the ambient air temperature. A maximum reduction of 4.2 °C was recorded as a result of incorporating green

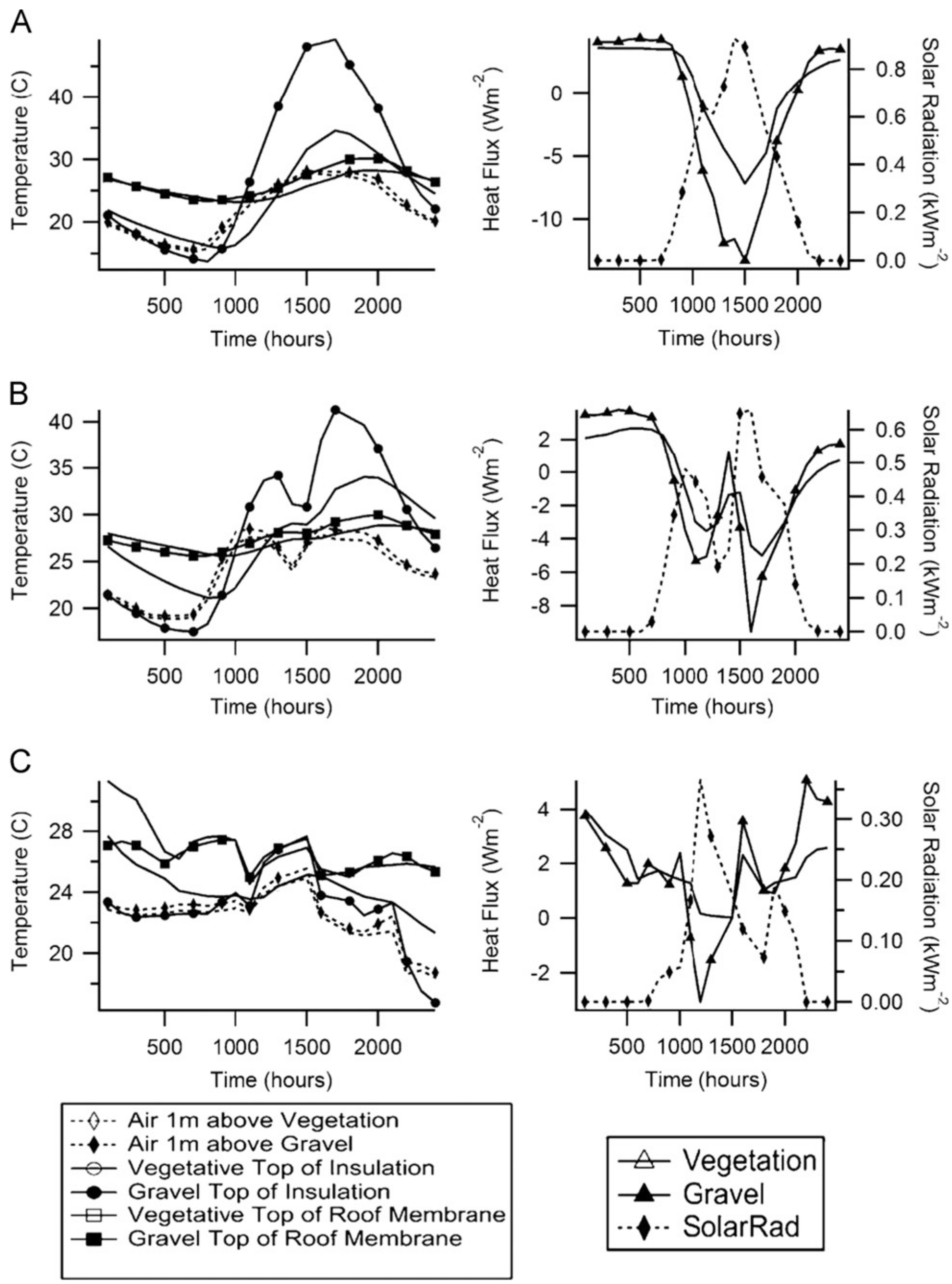

Fig. 9. Temperature and heat flux data over one day period for different environmental conditions in summer [85]. (A) Summer sunny (07 August 2006); (B) Summer cloudy (02 July 2006); (C) Summer rainy (2 August 2006).

roofs in their study [81]. Comparing the global temperatures and mean radiation temperature revealed that green roofs emit less long-wave radiation than normal roofs [81]. The maximum difference between mean radiation temperature and global temperatures appeared to be around 4.05 °C which is a good indicator on the efficiency of green roof in combating heat island effect [81].

Alexandri and Johns, undertook a computation modelling study through prognostic microscale model written in C++. They aimed to investigate the effects of green roofs and green walls in nine different cities. These cities included London, Montreal, Moscow, Athens, Beijing, Riyadh, Hong Kong, Mumbai and Brazil. These cities have diverse climatic characteristics and are in different geographical locations (see Table 3).

The results of their study showed that in all nine examined cases, the greatest decrease in cooling with magnitude of 100%, occurs in Brazil and Hong Kong [49]. London and Moscow were found not to be affected since they were cool enough on the day of measurement [49]. Meanwhile Riyadh showed 90% cooling load decrease, Montreal 85%, Mumbai 72% decrease, Athens 66%, and Beijing 64%, respectively [49]. Green roof system in combination with green wall system has been proven to decrease the total hours of cooling demand of various cities. For instance, utilization of this strategy in Riyadh and Montreal changes the cooling demand from 12 to 5 and from 8 to 4 respectively.

The study also revealed that for the hot and arid climate i.e. Riyadh, combination of green roofs and green walls can regulate the temperature in a range of 12.8–26.0 °C during daytime [49]. Their study concluded that use of green roofs in the mega scale i.e. city level could mitigate rise in urban temperatures. This strategy is proven to be more efficient in hot climates in decreasing the ambient temperatures to more "human-friendly" temperature and reducing cooling load by 32% to 100% [49].

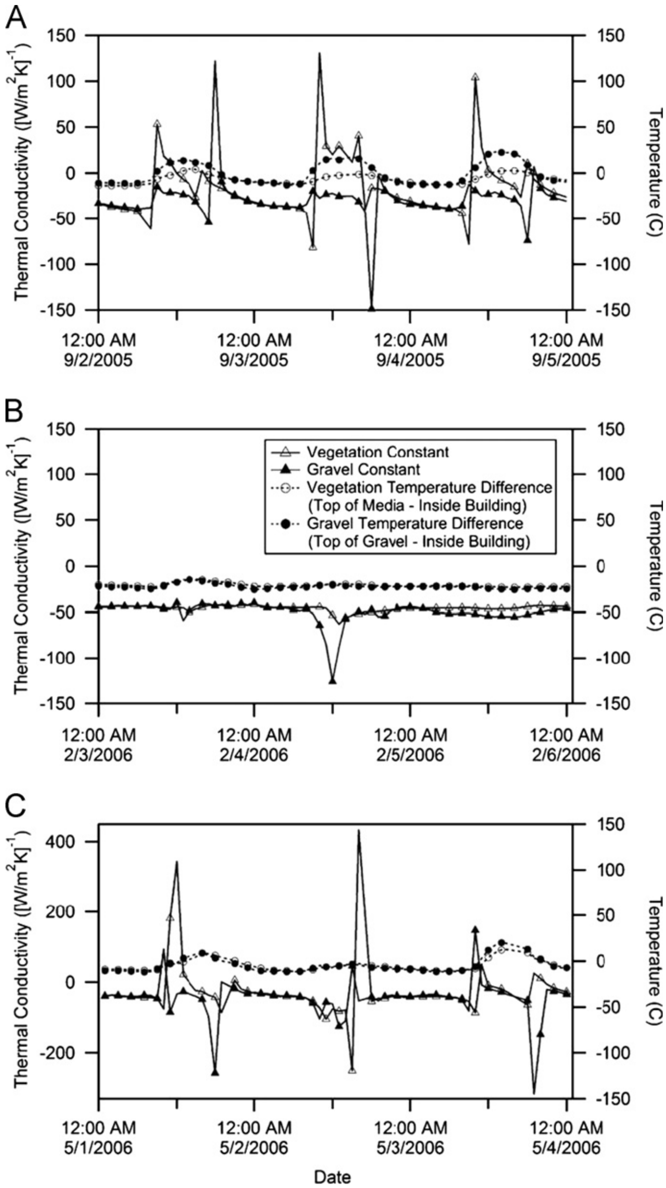

Fig. 10. Proportionality ratio between temperature and heat flux for: (A) 2–4 September 2005; (B) 3–5 February 2006; (C) 1–3 May 2006 [85].

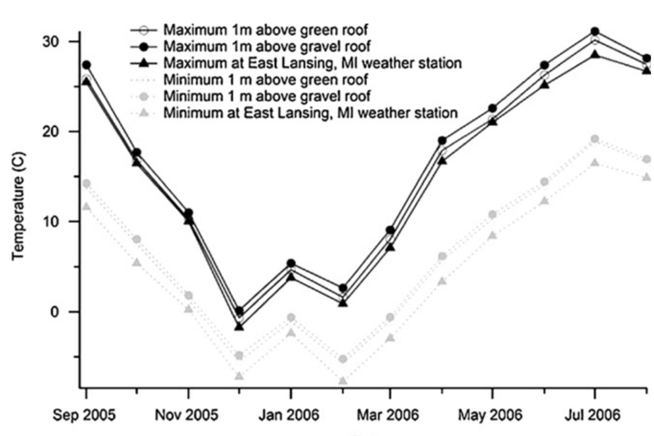

Fig. 11. Monthly average maximum and minimum air temperatures (°C) for the experimental building with various roofs and a nearby weather station [85].

Table 2
Monthly and seasonal cumulative heat flux for the various types of roofs [86].

Months	Cumulative heat flux (W/m^2)		Monthly cumulative heat flux averaged over a season (W/m^2)		Percentage of seasonal average reduction	Season
	Roof garden	Gravel roof	Roof garden	Gravel roof		
Jun	347	−74	220	−327	167	**Summer**
July	99	−540				
August	215	−367				
March	163	218	591	610	3	**Spring**
April	440	620				
May	1170	993				
December	3061	3430	2623	3017	13	**Winter**
January	909	1134				
February	3899	4487				
November	1224	427	2272	2164	−5	**Autumn**
October	2244	2357				
September	3349	3708				

Table 3
Specifications of case studies [49].

City	Geographical location	Type of climate
Montréal, Canada	45.31N, 73.34W	Subarctic
Moscow, Russia	55.45N, 37.37E	Continental cool summer
Riyadh, Saudi Arabia	24.38N, 46.43E	Desert
Hong Kong, China	22.16N, 114.12E	Humid subtropical
Mumbai, India	18.54N, 72.5E	Rain forest
Brasília, Brazil	15.48S, 47.54W	Savannah
London, UK	51.32N, 0	Temperate
Athens, Greece	37.59N, 23.43E	Mediterranean
Beijing, China	39.48N, 116.23E	Steppe

Comparison of green roofs and green walls indicated that green roofs have greatest effects than green walls in urban scale in tackling heat island effect [49].

Santamouris et al. [40] carried out another study on a green roof system installed in a nursery school building in Athens capital of Greece. They employed an experimental method and a mathematical model to investigate the energy and environmental performance of green roofs.

They calculated both the cooling and heating load of two periods including summers and winters. The results of the study revealed that green roofs produce a significant reduction of building's cooling load during summer. The reduction of building's cooling load was reported to be 6–49% for the whole building. However, for its last floor, it was between 12% and 87%. More interestingly, green roofs appeared to have no interference in the building shell for heating loads in winter.

4.4. Green roofs and heat flux

By and large, shading of plant canopy [11], insulation of the soil, and transpirational cooling of roof garden's plants reduce the magnitude of heat flux magnitude in green roofs [85,93]. Latent heat loss and improved reflectivity of incident solar are two main parameters of green roofs that cool buildings via the radiation [64]. In this regard albedo is defined as the ratio of total reflected solar rays to incident electromagnetic radiation [64]. Green roofs are regarded as a medium that can reduce the temperature of a roof. For instance a green roof can reduce the temperature of a black roof from 80 °C to 27 °C [64]. The efficiency of green roofs has been regarded as equal to the brightest possible white roofs [64].

The albedo of green roofs range from 0.7 to 0.85 which is much higher than albedo of a typical, 0.1–0.2, bitumen, tar, and gravel roofs.

Wong et al. [81] conducted a field measurement on bare roofs, and realized that in tropical climates the accumulated daytime heat entering the building was released during nighttime. However, green roofed buildings suffered less from this phenomenon [81]. The research team measured the air temperature in different heights above the green roof to investigate its thermal changes of ambient air temperature. The results of their study indicated that hard ground of the roofs reradiated the stored heat and warm up the ambient air whereas the green roof reduced the ambient air temperature drastically and even continued to reduce the ambient air temperature throughout the night [81].

Another research team, from the National Research Council of Canada, used a heat flux transducer instrument to measure the heat gain under different vegetations and for various seasons [94]. In their study, they compared two different green roof systems, each with 75–100 mm of light weight growing medium and a steel decked reference roof.

The outcome indicated that green roofs in Canada could reduce the heat gain by an average of 70–90% in summers and could prevent heat loss by 10–30% during winters [94]. The research team installed some thermocouples in different depths throughout the structure. The green roof was able to reduce the roof membrane peak temperatures and impose a 5 h delay from 2 p.m. to 7 p.m. [94]. A comparison between reference roof and typical green roof in summer is presented in Fig. 12 [94]. Five different lines are drawn in Fig. 12 where E0 is the interior thermocouple, E3 installed under the waterproof membrane, E4 placed under the soil, and E5 placed in the middle of the growing medium respectively. In this graph, OUT indicates the outside temperature.

This graph proves that a green roof imposes delay in temperature peak and it also reduces the overall temperature. The reason behind this delay is reported to be the thermal mass effects of green roofs [19]. Moreover, the presence of a substantial insulation layer presented that just a small proportion of the heat flux reduction is translated to a reduction in internal temperature [19].

4.5. Effects of growing medium's characteristics

Characteristics of growing mediums are considered as one of the main parameters that contribute to the efficiency of green roofs [95]. Depth of growing medium, its density and its humidity are among these characteristics. Density has a positive effect on thermal performance of green roofs. If the density of the growing medium increases, the thermal conductivity and hence heat flux of the soil will also increase [64]. Moreover, additional air pockets will increase the insulating properties of the growing medium.

In order to investigate the effects of the growing medium, a study was conducted on the depth and colour of the growing medium of green roofs by National Research Council of Canada. Their results showed that deeper green roofs produces lower heat gain and loss than green roofs with shallow growing medium [94]. In other words thicker substrate performs better in terms of thermal performance.

Another group of scientists, based in Singapore, employed DOE-2 energy simulation programme to investigate the thermal performance of a five story building [61]. They realized that every 10 cm increase in soil thickness increased the thermal resistance of dry clay soil by 0.4 m^2 K/W.

Growing medium moisture also alters the efficiency of green roofs through changing insulations properties and cooling the roof via evaporative cooling. Some scientists believe that wet green growing mediums functions as better insulators. Wet green growing mediums also increase the heat flux of the roof [64]. Nevertheless, some other scientists argued that wet growing mediums are poorer insulator compared to dry growing mediums since air is a better insulator than water [64].

A study was conducted by a group of Chinese researchers in China to investigate the role of evaporative cooling and growing medium moisture content [96]. They employed a mathematical model which was validated by a field experiment within 24 h of a typical summer day. Their results demonstrated that, when growing medium is almost saturated in the water, evapotranspiration of the plants and soil system accounted for 58.4% of the solar gain [96]. Meanwhile, 1.2% of the total heat is stored by plants and soil, or transferred into the spaces beneath [96].

Another research team investigated the role of evapotranspiration with measurements of a hospital building [97]. They employed simulation software and collected experimental data for the driest and the wettest periods of the summer season. Their model was a finite difference model for calculating the main system fluxes.

Their study aimed to compare the fluxes for three types of roofs namely dry green roofs, wet green roofs and insulated roofs without greening. The study revealed that the heat lost through evapotranspiration for a dry green roof is less than half of a wet green roof. They also concluded that the value of evapotranspiration differs for various climates. Moreover, their study results indicated that, the dry green roof reduces the incoming heat flux by 60% more than the traditional roof. Likewise, the study revealed that the wet roof provides additional evapotranspiration. This additional evapotranspiration has dual functions. Firstly, it prevents the heat flux into the building. Secondly, it acts as a passive cooler by removing heat from the building [97].

According to Castleton et al. [64] the humidity of the growing mediums causes evapotranspiration which affects the extent of heat lost. In cases of more humid growing medium, heat is drawn out of buildings more easily. The fact is that out of the building shield, evapotranspiration effects are higher than inside. In other

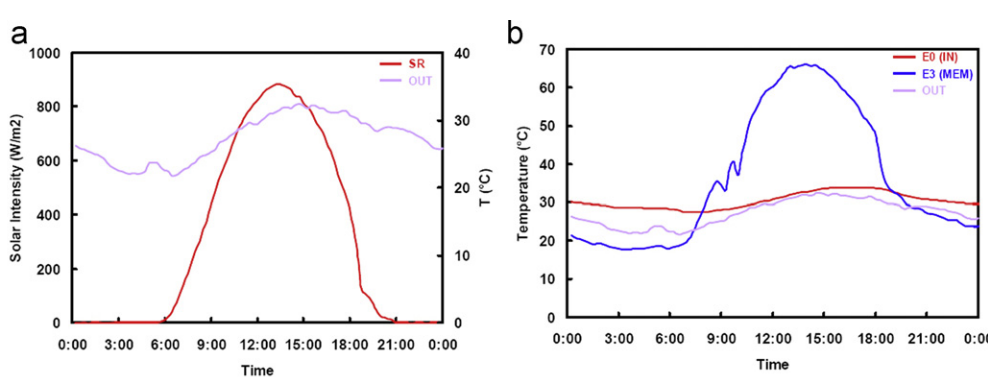

Fig. 12. Temperature profile in summer for a reference roof and intensive green roof [94]. (a) Ambient Conditions and (b) Reference Roof-Temprature.

Table 4
Comparison of three different roofs starting from 100 incident solar irradiation units summer session [98].

Energy related parameters	Type of roofs		
	Dry roof garden	Wet roof garden	Traditional roof
Incident solar radiation	100	100	100
Solar reflectivity	23	23	10
Solar absorption	39	39	0
Outside adduction	24	13	86
Evapotranspiration	12	25	0
Thermal accumulation	1.3	0.6	0
Inside adduction	1.8	0.4	4.4

words, dryer growing medium conditions act as better thermal insulations. Humidity also increases the conductivity of growing mediums (Table 4).

4.6. Effects of materials

Although the scope of this study is energy and the inclusion of materials may be considered deviation from this scope, product of materials and emission of materials is interlinked to energy [98] therefore it is included it in this review.

Two researchers, conducted a life cycle analyses on green roofs [74]. They aimed to evaluate the environmental benefits of green roofs by employing various research techniques. Those techniques included conducting interviews with experts, attending industrial workshops, distributing questionnaire survey among green roofs' experts and eventually use of SimaPro software. They compared emissions of NO_2, SO_2, O_3 and PM_{10} in green roofs' materials manufacturing process, like various types of polymers.

Comparing two types of polymer materials namely recycled LDPE and non-recycled LDPE revealed that the former releases 2.8 times less toxic substances to air than latter [74]. It also revealed that the four released toxic substances of NO_2, SO_2, O_3 and PM_{10} from the non-recycled LDPE are higher than the emissions from recycled process.

The research also exposed that extensive roof gardens release least amount of toxic substances. That is for both recycled and non-recycled materials. The reason behind it is that extensive roof gardens require less material than intensive roof gardens due to its thinner layers. However, intensive roof gardens usually have bigger plants and have a higher air dilution rate. Hence they have a better performance in the life cycle analysis. Their study concluded that the pollution from the production process of the green roof's polymers can be balanced by green roofs benefits in the long term. Nevertheless, due to high negative environmental impacts of low density polyethylene and polypropylene, it is essential to explore more environmentally friendly materials.

Another research team from Spain conducted an experimental method to explore the use of rubber crumbs in green roofs emphasizing on its energy and environmental benefits [99]. They investigated the possible use of this material as drainage layer in roof gardens instead of the porous stone materials. They studied the suitability of rubber crumbs for draining and they compared it with that of stone materials in terms of optimum balance rate between air and water. They employed an experimental research technique on August–September 2010 in the South of Reunion Island, in Saint-Pierre town. They found out the use of rubber crumbs saved a big amount of energy in comparison to the use of current commercial materials due to the difference in energy need of the transformation process. Besides, it provides solution to the problem of disposing waste tires. They also learnt that rubber crumbs are good substitutes for stone materials used as drainage layer in terms of insulation.

4.7. Green roofs and heat island

The temperature of cities goes up as a result of heat island which deteriorates comfort conditions of habitants. Heat island also intensifies the current energy problem of urban areas, endanger the vulnerable population like elders and sick people in summer. Green roofs are mediums that combat heat island and increase the albedo of urban areas. A study has carried out to compare the effects of green roofs and high reflection roof on heat island [100]. In this study, the surface temperature, water content ratio, amount of net radiation, of green roofs and high reflection roofs are resulted to heat and water budget are recorded and compared. On the green surface, the sensible heat flux is small because of the large latent heat flux by evaporation, although the net radiation is large. However, it showed functional in reducing heat island and cooling the temperature of a particular area [100].

A review of ten simulation studies indicates that green roofs can increase the city's albedo whereby, 0.1 increase of the albedo can decrease the average ambient temperature around 0.3 K and decreases the peak ambient temperature around 0.9 K [101]. Likewise, some simulation studies indicate that green roofs may reduce the average ambient temperature between 0.3 and 3 K in city scale and reduce heat island effects drastically [101].

Another study was conducted to analyse effects of green roofs in heat island by observing recent vegetated and reflective surfaces in LANDSAT images of Chicago in USA. Results show that applying green roofs and other vegetation forms in this city from 1995 increases the city's albedo, up to 0.016 [102]. Likewise, citywide Normalized Difference Vegetation Index (NDVI) rises up to 0.007. This finding along with counts of pixels with increased albedo and NDVI suggest that green roofs are very important in preventing heat island however, the reflective strategies are more useful than the vegetative methods [102].

4.8. Acoustic performance of green roofs

Although Acoustic performance of green roofs is not in the scope of this study, it provides insight on the performance of this technology. Acoustic performance of green roofs is an advantage of green roofs which is associated with noise reduction. It includes reducing the impact of external noise and in particular 'rain hammer' [103]. The reason is that green roofs improve the insulations properties of buildings [103]. This improvement happens because green roofs provide additional mass, low stiffness and induces damping effects [103].

Various kinds of green roofs systems function differently in preventing impacts of sounds. It is related to diffracted sound waves. A study conducted using a series of measurements of sound pressure level in a semi-anechoic chamber aimed to investigate acoustic performance of green roofs. In the chamber 20 green roofs trays consisting of the Zinco substrate with a depth of 100 mm and low-growing vegetation were used to address the above aim [104]. The experimental results imparted that green roofs drastically reduce noise at street in urban spaces for diffracted sound waves [104].

Another study was undertaken to investigate the potential of wall vegetation systems, green roofs, vegetated low screens at roof edges, and also combinations of those vegetations. They used combining 2D and 3D full-wave numerical method to analyse the road traffic noise propagation towards the traffic-free sides of the courtyards [105]. The results indicated that greening of the upper storeys in the street and (full) façades in the courtyard itself is most efficient to achieve noise reduction [105].

4.9. Maintenance of green roofs and energy

Green roofs have multiple environmental benefits and are widely used around the world. However, maintenance issues of green roofs are a matter of debate [106]. Maintenance of a green roof is not directly related to energy but it is one of the parameters of its life cycle analysis.

A study conducted on a life cycle analysis of a 120-year-old house to partially address this section's topic. Two various design of house with green roof and house with white roof were studied at a 10-year-of-roof-maintenance cycle [106]. The findings of the study imparted that house with green roof requires more retrofit embodied energy than house with white roof. The reason is that formers need more energy for soil transportation; ceiling replacement, roof joist retrofit kit, and soil pan fabrication, whereas the latter need solely energy for paint [106]. However, considering a 10-year period, house with the green roof consumes less energy versus house with white house even with higher maintenance energy consumption [106].

A study in Taiwan reviewed policies in regards to promoting green roofs development and compared them with other countries worldwide [107]. The study concluded that there is no significant additional maintenance energy consumption in tropical areas. The reason is that in urban cities of tropical countries, there exist a high runoff and associated mass loading [107].

Another study investigated maintenance energy use of green roofs, by considering different climates, intensity of rainfalls, types of building, various vegetations and several external coatings [108]. The result of their study indicates that the scarce amount of rainfall increase maintenance energy consumption because it needs additional watering [108]. Furthermore, one study in Poland using Life Cycle Cost (LCC) analysis confirmed the above findings [109]. Finally classical LCA methodology was conducted on green roofs [110]. Considering contribution of production, maintenance and end of life to the whole environmental burden of extensive green roofs it was concluded that the previous research had not sufficiently investigated maintenance issue because they had overlooked the role of fertilizer in doing LCA [110].

5. Summary and discussion

Green roofs, solar walls [111], wind catchers [112,113], double glazing windows [114], green walls [114], turbine and solar panels [112] are some sustainable approaches designed to combat energy crisis. The scope of this study is only green roofs and therefore we only focus on this architectural feature.

A green roof is a green component of building industry which includes roof with solar panels or vegetation. It is also called eco-roof, living roof, and roof garden. Historically, Europeans were the paradigm in the utilization of green roofs in their building led by Germany as a pioneer. There are two different types of green roofs known as intensive green roofs differencing in type of vegetations. The four main components of green roofs are: 1—water proofing membrane and filter membranes, 2—drainage films, 3—growing medium, and 4—vegetations. There are many advantages and few disadvantages in utilizing green roofs technology which will be explained in next paragraphs. In terms of water related issues, green roofs decrease storm water runoff, decreases the burden of water treatment facilities, and increase the water runoff quality. However, some of green roofs need water for irrigation and increases the water consumption.

In terms of noise related subjects, this architectural feature combats noise pollution and Reduces noise annoyance by road traffic. In regards to air quality, it produces more oxygen and sequesters carbon dioxide. It also creates habitats for wildlife which is important for ecosystem. In regards to human interaction, green roofs provide recreational opportunities, add aesthetical values and improve the urban quality.

In term of economic, green roofs it saves money particularly in terms of runoff water and energy, however, the initial cost of green roofs is more than three to six times of the conventional roofs. However, green roofs provide the following advantages in term of energy. It saves energy for cooling and air-conditioning, save energy due to higher thermal mass of the roof system and combat heat island. Green roofs also have the same efficiency in term of heat flux as the brightest possible white roofs; increase the roof's life and saves energy for manufacturing a new roof. Green roofs also reduces the ambient air temperature in daytime, reduces the ambient air temperature in nighttime, saves energy due to increment of shading and saves energy due to increment of shading.

These architectural features also save energy due to better insulation, improves the thermal comfort of occupants in hot climate, reduces the building temperature up to 20 °C, damper the solar radiations by absorbing 60% of them through photosynthesis, reduce the air-conditioning energy between 25% and 80%, and absorb lower irradiative temperature in comparison to other types of roofs.

Furthermore, they decrease the surface temperature of the roof around 30–60 °C, cause a lower heat flux leaving the building during chilly and moist conditions, protect the roof's membrane from rapid cooling and freezing in autumn and spring, and provide effective thermal insulation in winter. Moreover, green roofs emit less long-wave radiation than normal roofs, mitigate raised urban temperatures in the mega scale i.e. city level and decrease the ambient temperatures in hot climates into more "human-friendly".

Finally, green roofs reduce cooling load by 32–100%, and reduce the temperature of a black roof from 80 °C to 27 °C. Despite all of aforementioned advantages the initial cost of green roofs are higher versus conventional roofs and also more energy are required to warm the indoor air in winter time [91].

Green roofs are not only considered as sustainable approach for new buildings development but also are appropriate retrofitting medium to tackle energy crises as well as to cover the poor insulation problems in old buildings. Green roofs save energy and consequently save money. This saving is subjected to various parameters such as type of green roofs, depth and composition of the growing mediums, type of climates, plant selections, type of irrigations and insulation specifications. The depth, density and humidity of the growing medium are three components of growing medium that contributes to its efficiency. Meanwhile, the leaf area index (LAI), stomatal resistance, height, fractional coverage, and albedo are five components of plant selections that contributes to its efficiency.

Green roofs have different efficiencies for four seasons. Nonetheless, its maximum efficiency is reported during summers. Controversially, performance of green roofs in winter time is a matter of debate where some scientists claimed it as a medium to save energy and some viewed it as a cause of more energy consumption. Whatever it is, there are four influential parameters in performance of green roofs in winter namely volumetric moisture content of the soil, solar radiation, ambient outside temperature and snow.

Use of various materials, as green roof's components, is reported to have different impact in terms of energy and environmental effects. The use of recycled materials is highly recommended.

6. Recommendation for future studies

Comprehensive study on the performance of green roofs in winter time for different climates is highly recommended. Its efficiency in winter is a controversial subject since it is regarded as a cause of the increase in energy consumption. Study on the use of indigenous vegetations for reducing water consumption

and increasing energy efficiency for different geographical regions is also recommended.

Furthermore, we suggest that more study on sustainable materials for roof membrane is undertaken. These materials should be more durable, and at the same time should produce less environmental impact during its life cycle.

The public attitude and preference study of people towards utilization of green roofs for different countries should be gauged as well.

References

[1] Bahgat G. Israel's energy security: the Caspian Sea and the Middle East. Israel Affairs 2010; 16:406–15.
[2] Solomon BD, Krishna K. The coming sustainable energy transition: history, strategies, and outlook. Energy Policy 2011;39:7422–31.
[3] Wan KKW, Li DHW, Liu D, Lam JC. Future trends of building heating and cooling loads and energy consumption in different climates. Building and Environment 2011;46:223–34.
[4] Levermore G. A review of the IPCC Assessment Report Four, Part 1: the IPCC process and greenhouse gas emission trends from buildings worldwide. Building Services Engineering Research and Technology 2008;32:349–61.
[5] Masoso OT, Grobler LJ. The dark side of occupants behaviour on building energy use. Energy and Buildings 2010;42:173–7.
[6] Hassid S. Developments in the residential energy sector in Israel. Advances in Building Energy Research 2011;5:71–9.
[7] Sailor DJ, Elley TB, Gibson M. Exploring the building energy impacts of green roof design decisions—a modeling study of buildings in four distinct climates. Journal of Building Physics 2012;35:372–91.
[8] Pearlmutter D, Rosenfeld S. Performance analysis of a simple roof cooling system with irrigated soil and two shading alternatives. Energy and Buildings 2008;40:855–64.
[9] Hoffman L, McDonough W. Green roofs: ecological design and construction. New York: Schiffer Publishing; 2005.
[10] Xu T, Sathaye J, Akbari H, Garg V, Tetali S. Quantifying the direct benefits of cool roofs in an urban setting: reduced cooling energy use and lowered greenhouse gas emissions. Building and Environment 2011;48:1–6.
[11] Tabares-Velasco PC, Srebric J. Experimental quantification of heat and mass transfer process through vegetated roof samples in a new laboratory setup. International Journal of Heat and Mass Transfer 2011;54:5149–62.
[12] Getter KL, Bradley Rowe D, Cregg BM. Solar radiation intensity influences extensive green roof plant communities. Urban Forestry & Urban Greening 2009;8:269–81.
[13] Sailor DJ. A green roof model for building energy simulation programs. Energy and Buildings 2008;40:1466–78.
[14] Ondimu SN, Murase H. Combining Galerkin methods and neural network analysis to inversely determine thermal conductivity of living green roof materials. Biosystems Engineering 2007;96:541–50.
[15] Voyde E, Fassman E, Simcock R. Hydrology of an extensive living roof under sub-tropical climate conditions in Auckland, New Zealand. Journal of Hydrology 2010;394:384–95.
[16] Badescu V, Sicre B. Renewable energy for passive house heating: II. Model. Energy and Buildings. 2003;35:1085–96.
[17] Francis RA, Lorimer J. Urban reconciliation ecology: the potential of living roofs and walls. Journal of Environmental Management 2011;92:1429–37.
[18] Getter KL, Rowe DB, Andresen JA. Quantifying the effect of slope on extensive green roof stormwater retention. Ecological Engineering 2007;31: 225–231.
[19] Carter T, Jackson CR. Vegetated roofs for stormwater management at multiple spatial scales. Landscape and Urban Planning 2007;80:84–94.
[20] Fioretti R, Palla A, Lanza LG, Principi P. Green roof energy and water related performance in the Mediterranean climate. Building and Environment 2010;45:1890–904.
[21] Villarreal EL, Bengtsson L. Response of a Sedum green-roof to individual rain events. Ecological Engineering 2005;25:1–7.
[22] Mentens J, Raes D, Hermy M. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? Landscape and Urban Planning 2006;77:217–26.
[23] Hilten RN, Lawrence TM, Tollner EW. Modeling stormwater runoff from green roofs with HYDRUS-1D. Journal of Hydrology 2008;358:288–93.
[24] Rowe DB. Green roofs as a means of pollution abatement. Environmental Pollution 2011;159:2100–10.
[25] Zhang X, Shen L, Tam VWY, Lee WWY. Barriers to implement extensive green roof systems: a Hong Kong study. Renewable and Sustainable Energy Reviews 2011;16:314–9.
[26] Getter KL, Rowe DB, Robertson GP, Cregg BM, Andresen JA. Carbon sequestration potential of extensive green roofs. Environmental Science & Technology 2009;43:7564–70.
[27] Li J-f, Wai OWH, Li YS, Zhan J-m, Ho YA, Li J, et al. Effect of green roof on ambient CO_2 concentration. Building and Environment 2010;45:2644–51.
[28] Lundholm J, Peck S. Introduction: frontiers of green roof ecology. Urban Ecosystems 2008;11:335–7.
[29] Currie B, Bass B. Estimates of air pollution mitigation with green plants and green roofs using the UFORE model. Urban Ecosystems 2008;11:409–22.
[30] Pandey S, Hindoliya DA, Mod R. Experimental investigation on green roofs over buildings. International Journal of Low-Carbon Technologies 2012;1:0–44.
[31] Berndtsson JC, Bengtsson L, Jinno K. Runoff water quality from intensive and extensive vegetated roofs. Ecological Engineering 2009;35:369–80.
[32] Czemiel Berndtsson J. Green roof performance towards management of runoff water quantity and quality: a review. Ecological Engineering 2010;36:351–60.
[33] Palla A, Gnecco I, Lanza LG. Unsaturated 2D modelling of subsurface water flow in the coarse-grained porous matrix of a green roof. Journal of Hydrology 2009;379:193–204.
[34] Alsup SE, Ebbs SD, Battaglia LL, Retzlaff WA. Heavy metals in leachate from simulated green roof systems. Ecological Engineering 2011;37:1709–17.
[35] Jim CY, Peng LLH. Weather effect on thermal and energy performance of an extensive tropical green roof. Urban Forestry & Urban Greening 2011;11:73–85.
[36] Emilsson T, Czemiel Berndtsson J, Mattsson JE, Rolf K. Effect of using conventional and controlled release fertiliser on nutrient runoff from various vegetated roof systems. Ecological Engineering 2007;29:260–71.
[37] Beck DA, Johnson GR, Spolek GA. Amending greenroof soil with biochar to affect runoff water quantity and quality. Environmental Pollution 2011;159:2111–8.
[38] Thi Hoang Duong T, Adin A, Jackman D, van der Steen P, Vairavamoorthy K. Urban water management strategies based on a total urban water cycle model and energy aspects—case study for Tel Aviv. Urban Water Journal 2011;8:103–18.
[39] Alsup SE, Ebbs SD, Battaglia LL, Retzlaff WA. Heavy metals in leachate from simulated green roof systems. Ecological Engineering 2011; 37:1709–17.
[40] Santamouris M, Pavlou C, Doukas P, Mihalakakou G, Synnefa A, Hatzibiros A, et al. Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens. Greece Energy 2007;32:1781–8.
[41] Ouldboukhitine S-E, Belarbi R, Jaffal I, Trabelsi A. Assessment of green roof thermal behavior: a coupled heat and mass transfer model. Building and Environment 2011;46:2624–31.
[42] Morau D, Libelle T, Garde Fo. Performance evaluation of green roof for thermal protection of buildings in Reunion Island. Energy Procedia 2012;14:1008–16.
[43] Dvorak B, Volder A. Green roof vegetation for North American ecoregions: a literature review. Landscape and Urban Planning 2010;96:197–213.
[44] Justyna CB. Green roof performance towards management of runoff water quantity and quality: a review. Ecological Engineering 2010; 36:351–360.
[45] Schrader S, Boning M. Soil formation on green roofs and its contribution to urban biodiversity with emphasis on Collembolans. Pedobiologia 2006;50:347–56.
[46] Henry A, Frascaria-Lacoste N. The green roof dilemma Discussion of Francis and Lorimer (2011). Journal of Environmental Management 2012;104:91–2.
[47] Yu C, Hien WN. Thermal benefits of city parks. Energy and Buildings 2006;38:105–20.
[48] Skinner CJ. Urban density, meteorology and rooftops. Urban Policy and Research 2006;24:355–67.
[49] Alexandri E, Jones P. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. Building and Environment 2008;43:480–93.
[50] Zhang X, Shen L, Wu Y. Green strategy for gaining competitive advantage in housing development: a China study. Journal of Cleaner Production 2011;19:157–67.
[51] Takebayashi H, Moriyama M. Surface heat budget on green roof and high reflection roof for mitigation of urban heat island. Building and Environment 2007;42:2971–9.
[52] Williams NSG, Rayner JP, Raynor KJ. Green roofs for a wide brown land: opportunities and barriers for rooftop greening in Australia. Urban Forestry & Urban Greening 2010; 9:245–251.
[53] Ignatieva M, Stewart G, Meurk C. Planning and design of ecological networks in urban areas. Landscape and Ecological Engineering 2011;7:17–25.
[54] Kosareo L, Ries R. Comparative environmental life cycle assessment of green roofs. Building and Environment 2007;42:2606–13.
[55] Shashua-Bar L, Pearlmutter D, Erell E. The influence of trees and grass on outdoor thermal comfort in a hot-arid environment. International Journal of Climatology 2011;31:1498–506.
[56] Van Renterghem T, Botteldooren D. In-situ measurements of sound propagating over extensive green roofs. Building and Environment 2011;46:729–38.
[57] Van Renterghem T, Botteldooren D. Reducing the acoustical fa§ade load from road traffic with green roofs. Building and Environment 2009;44:1081–7.
[58] Yang HS, Kang J, Choi MS. Acoustic effects of green roof systems on a low-profiled structure at street level. Building and Environment 2012;50:44–55.
[59] Van Renterghem T, Botteldooren D. The importance of roof shape for road traffic noise shielding in the urban environment. Journal of Sound and Vibration 2010;329:1422–34.
[60] Booth C, Hammond FN, Lamond J, Proverbs DG. Solutions for climate change challenges of the built environment. John Wiley & Sons; 2012.
[61] Wong NH, Cheong DKW, Yan H, Soh J, Ong CL, Sia A. The effects of rooftop garden on energy consumption of a commercial building in Singapore. Energy and Buildings 2003;35:353–64.
[62] Ouldboukhitine S-E, Belarbi R, Djedjig R. Characterization of green roof components: measurements of thermal and hydrological properties. Building and Environment 2012;56:78–85.

[63] Nyuk Hien W, Puay Yok T, Yu C. Study of thermal performance of extensive rooftop greenery systems in the tropical climate. Building and Environment 2007;42:25–54.
[64] Castleton HF, Stovin V, Beck SBM, Davison JB. Green roofs; building energy savings and the potential for retrofit. Energy and Buildings 2010;42:1582–91.
[65] Justyna CB. Green roof performance towards management of runoff water quantity and quality: a review. Ecological Engineering 2010;36:351–60.
[66] Wilkinson SJ, Reed R. Green roof retrofit potential in the central business district. Property Management 2009;27:284–301.
[67] Blackhurst M, Hendrickson C, Matthews HS. Cost-effectiveness of green roofs. Journal of Architectural Engineering 2010;136.
[68] Schumann LM. University of Maryland CPBRE. ecologically inspired design of green roof retrofit. College Park: University of Maryland; 2007.
[69] Acks K. A framework of cost–benefit analysis of green roofs: initial estimates. New York: Columbia University Center for Climate Systems Research and NASA Goddard Institute for Space Studies; 2006.
[70] Clark† C, Adriaens P, Talbot FB. Green roof valuation: a probabilistic economic analysis of environmental benefits. Environmental Science and Technology 2008;42:2155–61.
[71] Saiz S, Kennedy C, Bass B, Pressnail K. Comparative life cycle assessment of standard and green roofs. Science and Technology 2006;40:4312–6.
[72] Stovin V, Hallam A. Green roofs-getting sustainable drainage off the ground. In: 6th International conference of sustainable techniques and strategies in urban water management; 2007. p. 11–8.
[73] Teemusk A, Mander U. Greenroof potential to reduce temperature fluctuations of a roof membrane: a case study from Estonia. Building and Environment 2009;44:643–50.
[74] Bianchini F, Hewage K. How green are the green roofs? Lifecycle analysis of green roof materials Building and Environment 2012;48:57–65.
[75] Oberndorfer E, Lundholm J, Bass B, Coffman RR, Doshi H, Dunnett N, et al. Green roofs as urban ecosystems: ecological structures, functions, and services. BioScience 2007;57:823–33.
[76] Emilsson T. Vegetation development on extensive vegetated green roofs: influence of substrate composition, establishment method and species mix. Ecological Engineering 2008;33:265–77.
[77] Emilsson T, Rolf K. Comparison of establishment methods for extensive green roofs in southern Sweden. Urban Forestry & Urban Greening 2005;3:103–11.
[78] Liu KKY, Baskaran BA. Thermal performance of green roofs through field evaluation. Chicago, IL: National Research Council Canada; 2003. p. 1–10.
[79] He H, Jim CY. Simulation of thermodynamic transmission in green roof ecosystem. Ecological Modelling 2010;221:2949–58.
[80] Jim CY, Tsang SW. Modeling the heat diffusion process in the abiotic layers of green roofs. Energy and Buildings 2011;43:1341–50.
[81] Wong NH, Chen Y, Ong CL, Sia A. Investigation of thermal benefits of rooftop garden in the tropical environment. Building and Environment 2003;38:261–70.
[82] Bowler DE, Buyung-Ali L, Knight TM, Pullin AS. Urban greening to cool towns and cities: a systematic review of the empirical evidence. Landscape and Urban Planning 2010;97:147–55.
[83] Shashua-Bar L, Potchter O, Bitan A, Boltansky D, Yaakov Y. Microclimate modelling of street tree species effects within the varied urban morphology in the Mediterranean city of Tel Aviv, Israel. International Journal of Climatology 2009;30:44–57.
[84] Yan B. The research of ecological and economic benefits for green roof. Applied Mechanics and Materials (Volumes) 2011;71:71–8.
[85] Getter KL, Rowe DB, Andresen JA, Wichman IS. Seasonal heat flux properties of an extensive green roof in a Midwestern U.S. climate. Energy and Buildings 2011;43:3548–57.
[86] Martens R, Bass B, Alcazar S. Roof–envelope ratio impact on green roof energy performance. Urban Ecosystems 2008;11:399–408.
[87] Wolf D, Lundholm JT. Water uptake in green roof microcosms: effects of plant species and water availability. Ecological Engineering 2008;33:179–86.
[88] Dvorak B, Volder A. Green roof vegetation for North American ecoregions: a literature review. Landscape and Urban Planning 2010; 96:197–213.
[89] Hodo-Abalo S, Banna M, Zeghmati B. Performance analysis of a planted roof as a passive cooling technique in hot-humid tropics. Renewable Energy 2012;39:140–8.
[90] Jaffal I, Ouldboukhitine S-E, Belarbi R. A comprehensive study of the impact of green roofs on building energy performance. Renewable Energy 2012;43:157–64.
[91] Jim CY, Tsang SW. Biophysical properties and thermal performance of an intensive green roof. Building and Environment 2011;46:1263–74.
[92] Spala A, Bagiorgas HS, Assimakopoulos MN, Kalavrouziotis J, Matthopoulos D, Mihalakakou G. On the green roof system. Selection, state of the art and energy potential investigation of a system installed in an office building in Athens, Greece. Renewable Energy 2008;33:173–7.
[93] Jim CY, Tsang SW. Ecological energetics of tropical intensive green roof. Energy and Buildings 2011;43:2696–704.
[94] Liu K, Minor J. Performance evaluation of an extensive green roof. Toronto: National Research Council of Canada; 2005.
[95] Rowe DB, Getter KL, Durhman AK. Effect of green roof media depth on Crassulacean plant succession over seven years. Landscape and Urban Planning 2012;104:310–9.
[96] Feng C, Meng Q, Zhang Y. Theoretical and experimental analysis of the energy balance of extensive green roofs. Energy and Buildings 2010;42:959–65.
[97] Lazzarin RM, Castellotti F, Busato F. Experimental measurements and numerical modelling of a green roof. Energy and Buildings 2005;37:1260–7.
[98] Molineux CJ, Fentiman CH, Gange AC. Characterising alternative recycled waste materials for use as green roof growing media in the U.K. Ecological Engineering 2009;35:1507–13.
[99] Vila A, Prez GCS, Fernandez AI, Cabeza LF. Use of rubber crumbs as drainage layer in experimental green roofs. Building and Environment 2011;48:101–6.
[100] Takebayashi H, Moriyama M. Surface heat budget on green roof and high reflection roof for mitigation of urban heat island. Environment 2007;1:2971–9.
[101] Santamouris M. A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Solar Energy 2012;30:12–28.
[102] Mackey CW, Lee Z, Smith RB. Remotely sensing the cooling effects of city scale efforts to reduce urban heat island. Building and Environment 2012;49:348–58.
[103] Asdrubali F, Schiavoni S, Horoshenkov KV. A review of sustainable materials for acoustic applications. Building Acoustics 2012;19(4):283–312.
[104] Yang H, Choi M, Kang J. Laboratory study of the effects of green roof systems on noise reduction at street levels for diffracted sound. In: Inter Noise, vol. 1, 2010. p. 23–43.
[105] Renterghem TV, Hornikx M, Forssen J, Dick B. The potential of building envelope greening to achieve quietness. Building and Environment 2013;61:34–44.
[106] Carpenter J, Zhou J. Life cycle analysis of a St. Louis flat roof residential retrofit for improved energy efficiency. Building Energy Use Modelling and Energy Efficiency 2013:20–8.
[107] Chen CF. Performance evaluation and development strategies for green roofs in Taiwan: a review. Ecological Engineering 2013;15:51–8.
[108] Ascione F, Bianco N, Rossi F, Turni G, Vanoli GP. Green roofs in European climates. Are effective solutions for the energy savings in air-conditioning? Applied Energy 2013;104:845–59.
[109] Sły D, Stec A, Zeleňáková MA. LCC analysis of rainwater management variants. Journal: Ecological Chemistry and Engineering 2012;3:359–72.
[110] Traverso GPM, Finkbeiner M, Rizzo G. Embedding substrate in environmental assessment of green roofs life cycle: evidences from an application to the whole chain in a Mediterranean site. Journal of Cleaner Production 2012;35:274–87.
[111] Saadatian O, Haw LC, Sopian K, Asim Nilofar, Sulaiman MY. Trombe walls: a review of opportunities and challenges in research and development. Renewable and Sustainable Energy Reviews 2012;16(2012):6340–51.
[112] Saadatian O, Haw LC, Sopian K, Sulaiman MY. Review of windcatcher technologies. Renewable and Sustainable Energy Reviews 2012;16:1477–95.
[113] Haw LC, Saadatian O, Mat Sohif, Sulaiman MY, Sopian K. Empirical study of a wind-induced natural ventilation tower under hot and humid climatic conditions. Energy and Building 2012;52:28–38.
[114] Saadatian O, Haw LC, Sopian K, Salleh E. A state of the art review of solar walls: concepts and applications. Building and Physics, http://dx.doi.org/10.1177/1744259113479336, in press.